

Charmed baryons from LHCb

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The vast amount of $c\bar{c}$ production that can be recorded by the LHCb detector makes it an ideal environment to study the hadronic production of charmed baryons, along with the properties of their decays. We briefly describe the LHCb experiment and the triggering mechanisms it uses for recording charm production. Previous charmed baryon results from LHCb are detailed, with a description of the future plans for the charmed baryon programme.

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1 Introduction

Recent years have seen great advances in our understandings of the charmed baryons. The B -factories, in particular the Belle and BaBar experiments, have been successful in making a wide variety of first observations of excited singly-charmed baryons [1, 2, 3, 4, 5, 6, 7, 8]. The current best knowledge of the spectra of singly-charmed baryons is given in Figure 1. The spin-parity assignments of many of the observed states are still to be discovered.

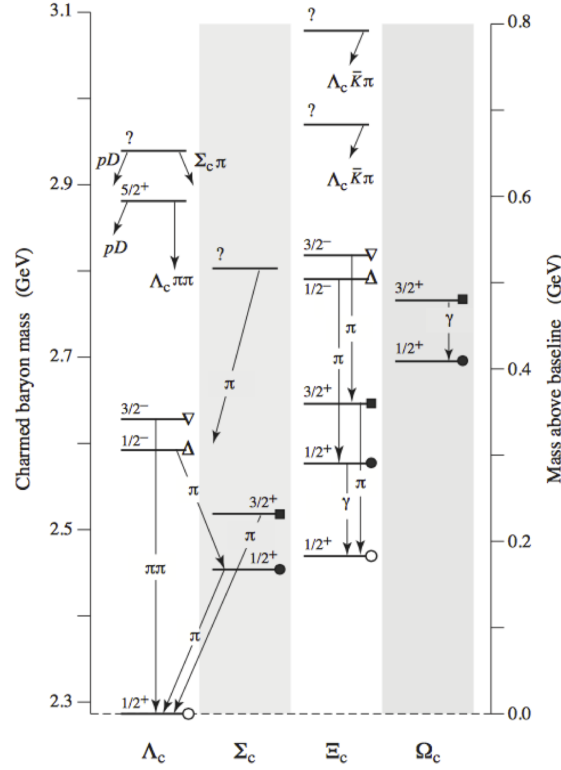


Figure 1: The spectra of known singly-charmed baryons and their mass splittings. Reproduced from [9].

In this document we briefly describe the LHCb detector and the strategies used in the triggering of charmed hadron production. We then describe an analysis measuring the prompt charm cross sections at $\sqrt{s} = 7$ TeV, including a measurement of the Λ_c^+ cross section. We describe a search for the doubly charmed baryon Ξ_{cc}^+ which was conducted with 0.65 pb^{-1} of 2011 LHCb data. We conclude by remarking on future analyses of charmed baryons that are planned at LHCb.

2 The LHCb detector

The LHCb [10] detector is a dedicated forward arm spectrometer and is the dedicated heavy-flavour physics experiment at the LHC. The detector has gathered large volumes of data from 2010 to 2012. The operating conditions of LHCb are given in Table 1 along with the original design specifications from the LHCb Letter of Intent [11]. These demonstrate that LHCb’s operating characteristics have significantly exceeded the original design, working at twice the instantaneous luminosity and recording events which are four times as complex as the design. This has resulted in LHCb being able to record vastly more charm production than originally envisaged, allowing for greater precision on our measurements. This data has already been utilised to make several important measurements in the charmed baryon sector, with many more new measurements presently being undertaken. These will be described in subsequent sections.

Year	\sqrt{s} [TeV]	Instantaneous \mathcal{L} [$\text{cm}^{-2}\text{s}^{-1}$]	μ	\mathcal{L}_{int}
2010	7	1×10^{32}	0.5 – 2.5	37 pb^{-1}
2011	7	4×10^{32}	1.5	1.0 fb^{-1}
2012	8	4×10^{32}	1.6	2 fb^{-1}
Design	14	2×10^{32}	0.4	-

Table 1: The LHCb running conditions throughout the LHC Run I and the nominal conditions. The pileup, μ , is the average number of $p - p$ collisions in each visible bunch crossing. The figures provided for the integrated luminosity, \mathcal{L}_{int} , are the integrated luminosity gathered in that year.

The detector possesses powerful resolution of secondary vertices from the decays of heavy-flavour particles produced in the primary interaction. Heavy flavour particles typically live long enough to fly around 1 cm from the location of the primary interaction. LHCb exploits a high-quality vertex resolution to isolate these particles from the production of lighter hadrons. The tracking system at LHCb provides a lifetime resolution of the order of 50 fs. The discrimination of interesting signals from the high backgrounds present in a hadronic production environment requires a precise mass resolution and therefore a precise momentum resolution. The tracking system at LHCb provides a momentum resolution of $\delta p/p \approx 0.4 - 0.6$ %.

Many decays of heavy-flavour hadrons of particular interest have a variety of topologically identical final states, obeying different CP symmetries. The discrimination between different species of charged particle is therefore of utmost importance. The particle identification (PID) system at LHCb is able to provide strong mass hypotheses over the momentum range 1 – 100 GeV.

3 The LHCb charm triggers

The production rate of $c\bar{c}$ in pp collisions at the LHC is much higher than it is in e^+e^- collisions at the B -factories. This has been measured at LHCb to be

$$\sigma(c\bar{c})_{p_{\text{T}} < 8 \text{ GeV}/c, 2.0 < y < 4.5} = 1419 \pm 12 \text{ (stat)} \pm 116 \text{ (syst)} \pm 65 \text{ (fragmentation)} \mu\text{b}$$

in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ for production below $8 \text{ GeV}/c$ transverse momentum and in the rapidity region $2.0 - 4.5$. The last error given is the uncertainty from the input fragmentation functions [12]. In Run I, 40 % of the 5 kHz trigger output rate was allotted to triggers for charmed hadrons. This presented a difficult challenge to retain as many interesting decays as possible given the constraints on trigger retention.

The LHCb trigger is comprised of a low level hardware trigger and a high level software trigger. This schema is illustrated in Figure 2. Specifically for hadrons, a cluster must be recorded in the calorimeter exceeding 3.5 GeV . The first level of the software trigger, the HLT1, exploits a partial reconstruction to quickly and efficiently identify tracks that are displaced from the primary proton-proton interaction point. For charmed baryon decays to hadronic states a single charged track is required to fulfil a series of track quality cuts. This track must also have a transverse momentum greater than $1.7 \text{ GeV}/c$ and an impact parameter with respect to the reconstructed primary interaction greater than 0.1 mm . At the second level of the software trigger, the HLT2, a full event reconstruction is employed, allowing the identification of displaced secondary vertices.

The PID information from the RICH detectors is also available at this stage. For decays of the short lived Λ_c^+ , where the candidate decay vertex is less displaced from the primary proton-proton interaction point than in D hadron decays, this was of key importance to reject combinations of unrelated tracks. The dedicated $\Lambda_c^+ \rightarrow pK^-\pi^+$ trigger in the HLT was one of a limited number of trigger lines which used PID information, to reject candidates where the proton track is a misidentified hadron of another species. Following this success, direct PID information in the HLT has now been implemented in a much wider variety of charm exclusive triggers for Run II.

Prompt charm is triggered with a series of exclusive lines which exploit hadronic signatures. A large number of secondary charm from b -hadron decays is also collected with a suite of inclusive b -hadron triggers. Notably, semileptonic b -hadron decays with muons in the final state can be used to exploit the high efficiency, high purity muonic triggers. The high production rate of charm necessitates a variety of requirements to be placed on candidates in order to reduce the trigger retention. These commonly consist of kinematic cuts on the c -hadron decay products, with vertex and track quality cuts.

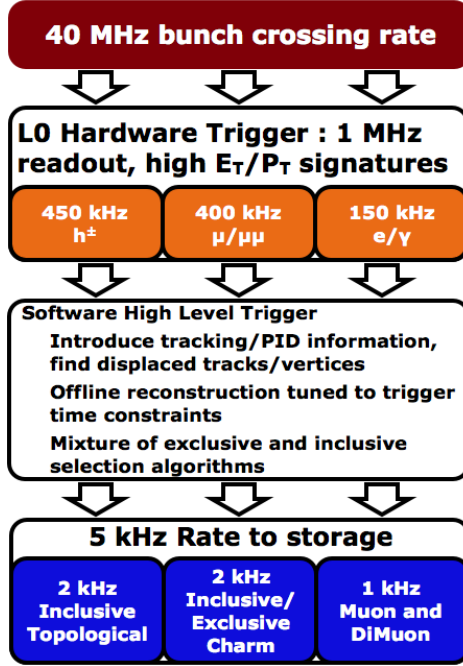


Figure 2: The LHCb trigger schema in Run I.

4 Λ_c^+ production cross-section at $\sqrt{s} = 7$ TeV

By measuring production cross-sections of charmed hadrons it is possible to test the predictions of quantum chromodynamics (QCD), specifically fragmentation and hadronisation models. Calculations of charm cross-sections at next-to-leading order made with the Generalized Mass Variable Flavour Number Scheme (GMVFNS) [13, 14] and at fixed order with next-to-leading-log resummation (FONLL) [15, 16, 17] have been shown to accurately reproduce the cross-sections measured both at the Tevatron [18] and the LHC [19, 20] in the central region ($|\eta| < 0.5$). LHCb offers a unique opportunity to study charm production in the forward region in pp collisions.

LHCb has published a measurement of the cross-sections of the D^0 , D^+ , D_s^+ , D^{*+} and Λ_c^+ at a center-of-mass energy $\sqrt{s} = 7$ TeV which was performed with 15 nb^{-1} of pp collisions recorded in 2010 [12]. Charm production at LHCb can be produced in a variety of ways - directly at the primary interaction, from feed-down of instantaneous decays of excited charm, and from secondary decays of b -hadrons. Those charmed hadrons produced in the first two ways are denoted as “prompt”, while those in the latter are denoted as “secondary” and are treated as a background in this analysis.

Candidate Λ_c^+ are selected with kinematic and PID criteria, and data-driven methods and simulation studies are used to evaluate the efficiency of the selection criteria. The signal extraction is performed with a simultaneous maximum likelihood fit to

the Λ_c^+ mass and the $\Lambda_c^+ \log(IP\chi^2)$. The fits are capable of discriminating among the prompt signal, the secondary background, and the backgrounds arising from random combinations of unrelated tracks. The results of the Λ_c^+ fit are shown in Figure 3, where the secondary contamination was found to be consistent with zero.

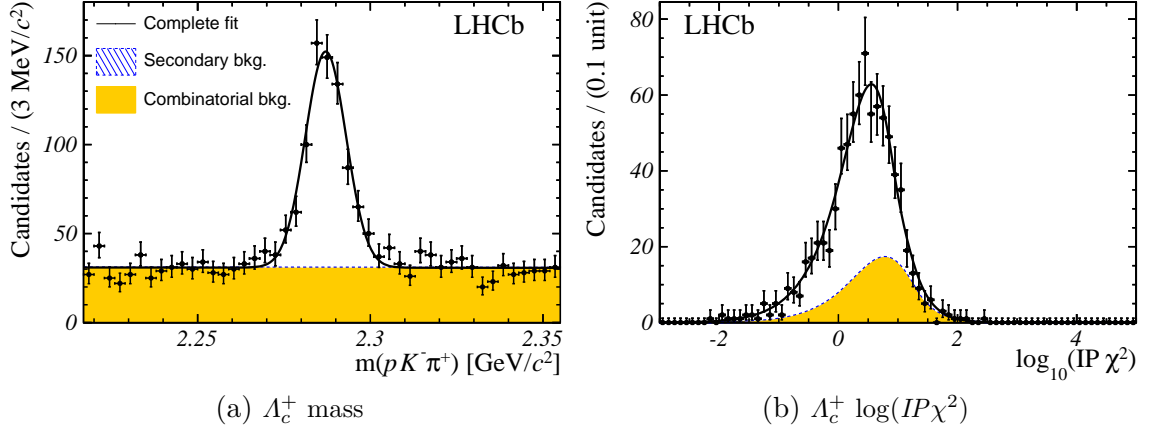


Figure 3: The fits used in the signal extraction of prompt Λ_c^+ from the combinatoric and secondary backgrounds.

The fiducial region of the measurement was 2–8 GeV/ c transverse momentum and rapidity 2.0 – 4.5. The Λ_c^+ data was divided into bins of p_T with one bin of rapidity, to allow comparison with the predictions from the GMVFNS scheme. The differential cross-section for Λ_c^+ in p_T bin i is calculated as

$$\frac{d\sigma_i(\Lambda_c^+)}{dp_T} = \frac{1}{\Delta p_T} \cdot \frac{N_i(\Lambda_c^+ \rightarrow pK^-\pi^+ + \text{c.c.})}{\epsilon_i(\Lambda_c^+ \rightarrow pK^-\pi^+) \cdot \mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) \cdot \mathcal{L}_{\text{int}}}$$

where $N_i(\Lambda_c^+ \rightarrow pK^-\pi^+ + \text{c.c.})$ is the number of $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays (and the charge conjugate mode) recorded in the bin, $\epsilon_i(\Lambda_c^+ \rightarrow pK^-\pi^+)$ is the selection efficiency in that bin, $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$ is the branching fraction of the decay (taken from the PDG as $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (5.0 \pm 1.3)\%$ [9]), and \mathcal{L}_{int} is the integrated luminosity of the data sample. The Λ_c^+ cross-section as a function of p_T is shown in Figure 4.

The total Λ_c^+ production cross-section in the fiducial region is calculated by discounting bins with a relative uncertainty larger than 50 % and extrapolating the cross-section with predictions from PYTHIA 6.4. We measure a total cross-section in the acceptance for the Λ_c^+ of

$$\sigma(\Lambda_c^+)_{p_T < 8 \text{ GeV}/c, 2.0 < y < 4.5} = 233 \pm 26 \text{ (stat)} \pm 71 \text{ (syst)} \pm 14 \text{ (extrapolation)} \mu\text{b}$$

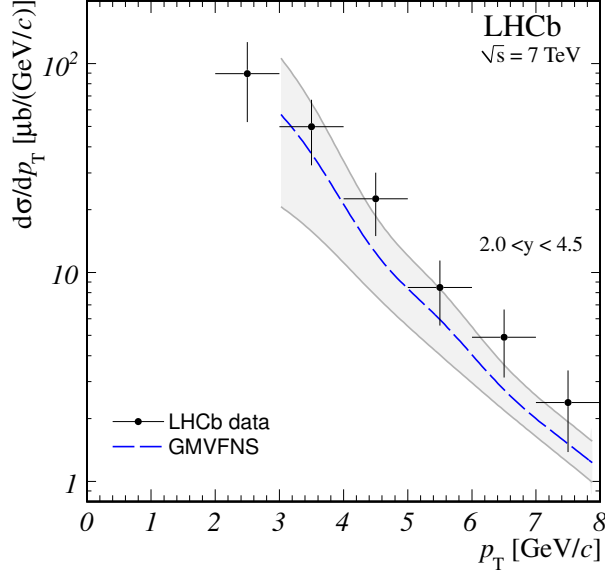


Figure 4: The measured Λ_c^+ cross-section as a function of the Λ_c^+ p_T , compared with predictions from the GMVFNS scheme. The error bars show the combined statistical and systematic uncertainty on the measurements and the shaded region indicates the uncertainty on the theoretical predictions.

5 Search for Ξ_{cc}^+ with 2011 data

For the $SU(4)$ multiplets of baryons composed of the u , d , s and c quarks we find states in the quark model corresponding to ccd (Ξ_{cc}^+), ccu (Ξ_{cc}^{++}) and ccs (Ω_{cc}^+). Theoretical calculations generally agree that the Ξ_{cc}^+ state should have lifetimes between 100 – 250 fs, with the Ξ_{cc}^{++} state having a lifetime between 500 – 1550 fs [21, 22]. Evaluations for the particle mass generally predict that the Ξ_{cc} isodoublet will have a mass between 3.5 – 3.7 GeV/ c^2 , with the mass of the Ω_{cc}^+ predicted to be between 3650 – 3800 GeV/ c^2 [23, 24, 25, 26].

The SELEX collaboration has reported observation of the Ξ_{cc}^+ in its decay to $\Lambda_c^0 K^- \pi^+$ [27] and evidence of the Ξ_{cc}^+ in the mode $p D^+ K^-$ [28]. The reported state has a measured mass of 3519 ± 2 MeV/ c^2 , consistent with predictions from the theory community. Its measured lifetime, however, was consistent with zero, and less than 33 fs at the 90 % confidence level. This is in strong disagreement with predictions of HQET and lattice QCD and is very different to the well-established lifetime of the Λ_c^+ ($\tau \approx 200$ fs).

If such an observation is legitimate, then much can be learned from the study of the baryon and the mechanisms that lead to its uncharacteristically short lifetime. Subsequent searches at notably BELLE [1], BaBar [29] and other experiments have not shown evidence for doubly-charmed baryon production. As such, the matter is

still very much open to discussion, and the theory community eagerly awaits a second experimental observation of the state.

LHCb has conducted the first search for doubly charmed baryon production at a pp collider [30]. This search was performed on 0.65 pb^{-1} of pp data gathered in 2011 at a centre-of-mass energy $\sqrt{s} = 7 \text{ TeV}$, using the decay mode $\Xi_{cc}^+ \rightarrow \Lambda_c^+(pK^-\pi^+)K^-\pi^+$ and the normalisation channel $\Lambda_c^+ \rightarrow pK^-\pi^+$. We specifically measure the ratio of Ξ_{cc}^+ production relative to Λ_c^+ production:

$$R \equiv \frac{\sigma(\Xi_{cc}^+)\mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}}$$

where σ and \mathcal{B} are the relevant cross-sections and branching fractions, N_{sig} and N_{norm} are the extracted yields of the Ξ_{cc}^+ signal and the control Λ_c^+ , and ϵ_{sig} and ϵ_{norm} are selection efficiencies.

To account for the unknown Ξ_{cc}^+ mass and lifetime we search for the Ξ_{cc}^+ in a wide mass range ($3300 - 3800 \text{ MeV}/c^2$), and calculate efficiencies for a variety of Ξ_{cc}^+ lifetime hypotheses. For each candidate we define a mass difference δm as

$$\delta m \equiv m([pK^-\pi^+]_{\Lambda_c^+}K^-\pi^+) - m([pK^-\pi^+]_{\Lambda_c^+}) - m(K^-) - m(\pi^+)$$

where $m([pK^-\pi^+]_{\Lambda_c^+}K^-\pi^+)$ is the measured mass of the reconstructed Ξ_{cc}^+ candidate, $m([pK^-\pi^+]_{\Lambda_c^+})$ is the measured mass of the reconstructed Λ_c^+ candidate and $m(K^-)$ and $m(\pi^+)$ are the charged kaon and pion world-averaged masses. The Ξ_{cc}^+ mass window in the analysis corresponds to a δm signal window of $380 < \delta m < 880 \text{ MeV}$.

The selection of candidates aims to reject backgrounds arising from combinations of unrelated tracks, mis-reconstructed c -hadron and b -hadron decays, and combinations of real Λ_c^+ with unrelated tracks. We first construct Λ_c^+ candidates, requiring that each passes a selection algorithm in the HLT that requires that the Λ_c^+ must be displaced from the primary interaction. The algorithm also places PID, kinematic and vertex/track quality requirements on the decay. Ξ_{cc}^+ candidates are then constructed by pairing the Λ_c^+ candidates with a kaon and pion track. The bachelor kaons and pions are required not to point back to the primary interaction. This diminishes the sensitivity of the selection in the case of a very short lifetime Ξ_{cc}^+ , but is necessary for the rejection of backgrounds where a real Λ_c^+ is paired with random kaons and pions. Finally, an artificial neural network is used to improve the selection purity of Ξ_{cc}^+ candidates, trained to have as little as possible sensitivity to the Ξ_{cc}^+ lifetime.

The signal yield of the normalisation channel is extracted with a fit to the $m(pK^-\pi^+)$ distribution. The normalisation yield was found to be $(818 \pm 7) \times 10^3$, with a signal width of $6 \text{ MeV}/c^2$. The Ξ_{cc}^+ yield is extracted with an analytic sideband subtraction that requires knowledge of the Ξ_{cc}^+ mass resolution (which is taken from simulation) but requires no other information of the Ξ_{cc}^+ lineshape.

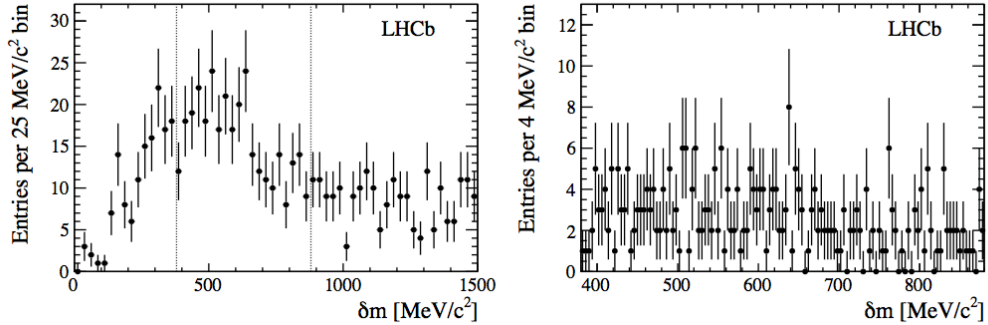


Figure 5: The full δm spectrum (left) and the Ξ_{cc}^+ signal region (right, marked with dashed lines on the full δm spectrum).

Signal yields are calculated in $1 \text{ MeV}/c^2$ intervals of δm across the full signal region. Local significances at each interval are given as:

$$\mathcal{S}(\delta m) \equiv \frac{N_{S+B} - N_B}{\sqrt{\sigma_{S+B}^2 + \sigma_B^2}}$$

where σ_{S+B}^2 and σ_B^2 are the statistical uncertainties on the signal yield and the expected background. Global significances for each δm must take into account the “look elsewhere effect” [31]. We do so by generating a large number of background only pseudo-experiments, with the full analysis method applied to each. We give a global p -value for a given S as the fraction of the total simulated experiments with an equal or larger local significance anywhere in the δm spectrum.

The largest local significance observed is $S = 1.5\sigma$ at a $\delta m = 513 \text{ MeV}/c^2$, corresponding to a global p -value for the null hypothesis of 99 %. We therefore give upper limits on R as a function of δm with the CL_S method [32]. We do so for a variety of Ξ_{cc}^+ lifetime hypotheses (arrived at by re-weighting the simulation-derived efficiencies with different generated Ξ_{cc}^+ lifetimes). These are given in Figure 6.

6 Future and ongoing projects

A great many charmed baryon analyses are currently underway at LHCb, covering a wide range of topics. We briefly describe some of these, including updates to the analyses presented herein. We also detail some future prospects for future LHCb datasets which will be collected in the LHC Run II and Run III.

Charm cross-section measurements at $\sqrt{s} = 13 \text{ TeV}$ are in progress with the 2015 LHCb dataset. We plan an expanded suite of measurements, including differential cross-sections of the Λ_c^+ , Σ_c^0 , Σ_c^{++} , Ξ_c^+ and Ξ_c^0 baryons. Work is also ongoing in

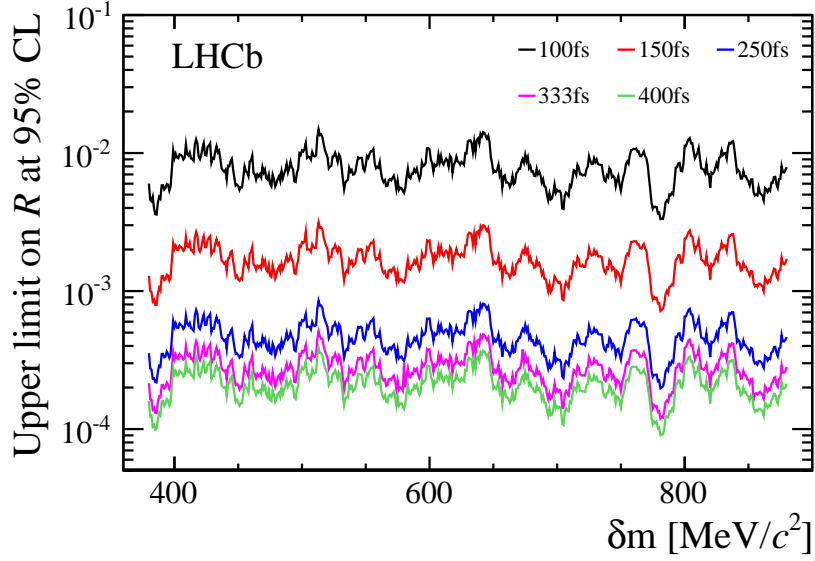


Figure 6: Upper limits on R for a number of Ξ_{cc}^+ lifetime hypotheses.

improving the description of the proton detection asymmetry at LHCb, which is a limiting factor in prospective production asymmetry studies of these baryons. We hope to perform these measurements with $\sqrt{s} = 13$ TeV data, complementary to our published results on D and D_s production asymmetries at LHCb.

A new search for the doubly charmed baryons with the full Run I dataset is underway. In addition to the Ξ_{cc}^+ , we now also search for the Ξ_{cc}^{++} . The analysis is able to take advantage of improvements to the dedicated $\Lambda_c^+ \rightarrow pK^-\pi^+$ triggers made in 2012 to enhance sensitivity. An expanded suite of Cabibbo-favoured decay modes will be used to search for these particles, including $\Xi_{cc}^{+[+]} \rightarrow D^+(K^-\pi^+\pi^+)pK^-[\pi^+]$ and $\Xi_{cc}^{+[+]} \rightarrow D^0(K^-\pi^+)pK^-[\pi^+]$ which can take advantage of LHCb's excellent D reconstruction. We tentatively expect to improve our current upper limits on R by an order of magnitude.

In addition to these powerful tests of the standard model, there exist promising avenues of investigating new physics with charmed baryons. Investigations of CP -violation and of rare decays with charmed baryons offer searches for new physics complementary to those conducted with charmed mesons due to the different strong phases in their decays. A search for CP -violation in Cabibbo-suppressed Λ_c^+ decays is currently underway using the Run I dataset. A search for the rare decay $\Lambda_c^+ \rightarrow p\mu^+\mu^-$ is also being conducted. In Run II we anticipate that charmed baryon CP -violation searches will have the same sensitivity as our CP -violation searches with charmed mesons from Run I. The suite of charmed baryon trigger lines has also been expanded for Run II to enable a wide variety of spectroscopy analyses. We also anticipate that observations of the Ξ_{cc}^+ should be possible at LHCb with the Run II dataset. Looking

ahead to Run III we anticipate excellent precision on CP -violation searches with charmed baryons. We also expect the ability to conduct double charm spectroscopy, and the ability to probe for the triple charmed baryon Ω_{ccc}^+ .

We conclude by reiterating that the LHCb detector’s ability to perform charmed baryon measurements has thus far been excellent. Over the course of the experiment’s lifetime we anticipate a wide number of measurements of charmed baryon branching fractions, masses and lifetimes. We also plan to search for the remaining charmed baryon states and are optimistic we can contribute to the open questions of doubly charmed baryon production.

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